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Integrated Constructed Wetlands (ICW) for livestock wastewater management

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ABSTRACT

Social, economic and environmental coherence is sought in the management of livestock wastewater. Wetlands facilitate the biogeochemical processes that exploit livestock wastewater and provide opportunities to achieve such coherence and also to deliver on a range of ecosystem services. The Integrated Constructed Wetland (ICW) concept integrates three inextricably linked objectives: water quantity and quality management, landscape-fit to improve aesthetic site values and enhanced biodiversity. The synergies derived from this explicit integration allow one of the key challenges for livestock management to be addressed. An example utilizing twelve ICW systems from a catchment on the south coast of Ireland demonstrates that over an eight year period mean reduction of total and soluble phosphorus (molybdate reactive phosphorus) exceeded 95% and the mean removal of ammonium-N exceeded 98%. This paper reviews evidence regarding the capacity of ICWs to provide a coherent and sustainable alternative to conventional systems.

1. Introduction

Worldwide, social, economic and environmental coherence is sought in the management of livestock wastewater (Steinfeld et al., 2006; Chadwick et al., 2008). This coherence is increasingly required in addressing problems of pollution to both surface and ground water resources from agricultural point and diffuse sources (Mainstone et al., 2008; USEPA, 2008). Achieving such coherence requires that the interlinked biogeochemical dynamics of atmosphere, water and soils are addressed. There is now a growing awareness of the capacities of certain types of wetlands, where these processes are optimally functional, with regard to achieving effective water management (Bullock and Acreman, 2003). These capacities include a range of environmental services such as the reduction of flooding, provisioning and safeguarding of water resources and improving water quality (Millennium Ecosystem Assessment, 2005; Maltby, 2009). More specifically, constructed wetlands are increasingly considered effective for the management of water quality issues relating to livestock wastewater (Knight et al., 2000; Cronk, 1996; Tanner and Kloosterman, 1997).

A common goal with regard to livestock waste management is the need for 'closed-loop' systems; making full use of the residual values of livestock waste in ways that do not impact negatively on the environment and that are both socially and economically acceptable. These goals principally include the retrieval of energy (Wilkie, 2006), or its sequestration as organic or chemical carbon (Fellman et al., 2008), the recycling of nutrients (Petersen et al., 2007) and, especially in drought-stressed regions, the reuse of water (Scott et al., 2004). These specific goals are sympathetic to the principles of the 'Ecosystem Approach' which promote a strategy for the integrated management of land, water and living resources, promoting nature conservation and sustainable use in an equitable way (Maltby, 2000). The principles enshrined in the Ecosystem Approach are increasingly seen as the framework for action with regard to sustainable water and natural resource management (Hartje et al., 2003; Apitz et al., 2006).

The rural location of most livestock enterprises and the fact that livestock wastewater is by its nature an appropriate substrate for further biological activity (Cantrell et al., 2008), provides an opportunity for integrated land and water management. One such combined approach was initiated in the mid 1990s in the Republic of Ireland whereby the concepts of restoration ecology (Jordan et al., 1987) were applied by largely mimicking the structure of shallow emergent-vegetated wetlands in the management of farmyard dirty water (Harrington and Ryder, 2002; Scholz et al., 2007). This approach was termed the 'Integrated Constructed Wetland' (ICW) concept (Harrington and Ryder, 2002). The evolving ICW concept combines various approaches to water, land and living resource management by explicitly integrating three objectives: water quantity and water quality management, including flood-hazard management; landscape-fit towards improving site aesthetic values; and the enhancement of biodiversity. The explicit integration of these three objectives is made with the expectation of achieving positive synergies that might not otherwise be achieved if traditional land management strategies had been

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adopted. The fundamental objective is the sustainable and holistic management of a diversity of wastewater, including livestock wastewater, and associated land and water resources. The ICW concept continues to be developed by applying the principles of adaptive management (Harrington et al., 2005).

Whilst initially developed for the Annestown stream catchment (c. 25 ha) in south County Waterford, Ireland, the ICW concept has potential for universal application (Carty et al., 2008). Within the European Union, the appropriate application of its principles has relevance in contributing towards Member States achieving good chemical and ecological status for inland and coastal waters by 2015 as required under EU Water Framework Directive (Commission of the European Communities, 2000).

Three factors are considered to be key when determining the successful application of constructed wetlands to the holistic management of livestock wastewater (Carty et al., 2008), namely: the ammonium-N concentration of the influent, and its effective removal through nitrification and de-nitrification; phosphorus capture and retention, which are generally considered to be the most wetland area-dependent parameters (Reddy et al., 1999; Pant et al., 2001); and whether local soil materials are capable of providing effective protection to underlying and associated ground waters. In this paper, these key factors in the ICW concept are explored and reviewed with regard to livestock wastewater management.

2. Wetland structure and function

A great diversity of wetlands exists (Finlayson and van der Valk, 1995). From this diversity, those classified as *palustrine*, *emergent wetlands* (Cowardin et al., 1979), with a shallow water depth (<20–40 cm), dense emergent vegetation, dominant anaerobic horizon, and high inherent capacity for primary macrophytic productivity are likely to be the most effective in the removal of through-flowing nutrients, suspended solids, pathogens and complex organic compounds when sized and configured appropriately (Verhoeven et al., 2006). Notwithstanding their environmental functionality, these types of shallow wetland are inherently highly vulnerable to drainage. They have been largely lost from most landscapes around the world where agriculture is practiced (Maltby and McInnes, 1997); indeed they are particularly sought out for their relatively higher nutrient status and productivity (Morris et al., 2000). So great has the loss of these wetlands been that their environmental services are today largely unrecognised (Zedler and Kercher, 2005).

Shallow emergent-vegetated wetlands may form wherever water-flow slows or remains long enough on the surface to allow anaerobic hydric soils to develop (Brinson, 1993). The plant and animal communities associated with such soils and accompanying shallow water conditions are distinctly different from terrestrial communities on largely permeable aerobic soils (Naiman and Décamps, 1997). The communities that occupy anaerobic hydric soils and associated flooded, shallow water have evolved a range of capacities and strategies to sustain their occupancy of these habitats (Blom and Voesenek, 1996). Research has shown that various evolutionary adaptations and associated feedback mechanisms operate to facilitate water retention by wetland plants by maintaining hydric anaerobic conditions and thus organic matter accumulation (Hobbie, 1992) or reducing evapotranspiration losses through the evolution of leaf characteristics more commonly associated with xerophytic habitats (Sytsma and Anderson, 1993). The biofilms and organic detritus that establish on newly created hydric soils further enhance water retention through reduction of permeability (Findlay and Sobczak, 2000). Similarly the physical processes of sedimentation and colmation may further reduce local permeabilities (Rehg et al., 2005). Poorly biodegradable polyphenolic compounds produced by macrophytes inhibit the decay of litter under the prevailing anaerobic conditions, allowing the accumulation of organic matter including that from the microbial necromass and organic influents (Freeman et al.,1996, 2001; Williams et al., 2000). These shallow emergent-vegetated wetland attributes provide a distinctly advantageous environment for the management of livestock wastewater by their sustainable capacity for retaining constituent organic matter and nutrients. In addition, they provide an effective environment for transforming ammonium-N to gaseous nitrogen (de Datta, 1995; McGechan et al., 2005).

The chemical and hydraulic status of a wetland is critical to its functional character with various vegetation types and component species interacting with water chemistry, depth and other physical characteristics (Hills et al., 1994). In the case of emergent-vegetated, shallow water wetlands (typically <200 mm) the dominant plant genera such as *Typha*, *Glyceria*, *Carex* and *Schoenoplectus*, facilitate water capture by rapidly shedding intercepted precipitation or water condensing on their foliage. This attribute, along with shading and lower air turbulence which decrease potential evapotranspiration (van der Valk, 2006; Sytsma and Anderson, 1993) facilitate the retention of water within the wetland system. The presence of these and other such feedback and facilitation processes demonstrate the inherent hydraulic integrity of wetland systems. In the context of wetlands used for the treatment of polluted water, when established, internal mechanisms will contribute to the retention of influent and the reduction of water losses from the system. This confidence is further strengthened by the consideration of the evolutionary background of the physical and chemical attributes that emergent plant species have evolved for life in hydric soils and associated anaerobic aquatic conditions of wetlands and their competitive 'fitness': primarily, the capacity to out-compete and avoid potential displacement by more terrestrial plant species (Harper, 1977; van der Valk, 2006).

Consideration of the combined effects of the physical, chemical and biological characteristics of a wetland, including microbial, plant and animal communities, is required to understand its hydrological and biogeochemical functioning (Maltby, 2009). The biota that are found in *emergent palustrine wetlands* support the structures and processes described above and indicate that they can provide a unique range of environmental services well suited to the sustainable management of many sources of polluted water including livestock wastewater (van der Valk, 2006).

3. Livestock wastewater: composition, volume and flow

Traditional methods of treating livestock wastewater involve lagoon retention and subsequent spreading on fields, but the sheer volume and variability of production is outstripping these and other technologies (Cressie and Majure, 1997). Livestock species, their type and age, the nature of their feed and how it is fed, whether or not the livestock are housed, weather and climate, all combine to effect wastewater composition, volume and its rate of production (Knight et al., 2000). Since they are not subject to the intermittent effects of precipitation, housed livestock with associated covered waste facilities will generally have a more uniform composition, constant and predictable flow than that from livestock on open yards or with waste-holding facilities that are open to the weather.

Climatic considerations for livestock wastewater management have special relevance. In arid zones livestock wastewater has less volume and higher concentrations than that in areas of high rainfall than where there is the additional influence of variation in the magnitude, a frequency and duration of rainfall events and inter-